6 mW and 30 mW laser threshold for respectively 1st and 2nd Brillouin Stokes order in a Ge10As24Se68 chalcogenide fiber

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Abstract *A compact second-order Stokes Brillouin fiber laser made of microstructured chalcogenide glass is reported for the first time. This laser has very low optical pump-power threshold for Stokes conversion: 6 mW for first order and only 30 mW for second order with nonresonant pumping.*

Introduction

Although stimulated Brillouin scattering (SBS) in optical fiber is a penalizing nonlinear effect in optical communication systems, it is possible to make good use of SBS in other applications such as in Brillouin fiber lasers (BFLs). These types of lasers have been attracting a lot of interests lately due to their extremely narrow linewidth [1] which make them perfect candidates for coherent laser sources.

Silica-based optical fibers are often used for these applications. However, due to the relatively small Brillouin gain coefficient g_B of 4×10^{-11} m/W in silica [2], optical fibers of several kilometers or pump power of several hundred milliwatts are required to reach Brillouin threshold.

One approach to make low-power consuming and more compact devices based on SBS is to use a material with a higher Brillouin gain coefficient. Chalcogenide fibers are an attractive option to make BFLs because of their high Brillouin gain coefficient, which is about 150 times more than in standard silica fibers [3]. In 2006, a BFL made of 4.9 m long step-index As_2Se_3 chalcogenide fiber was mentioned [4]. This laser had a threshold of 35 mW for nonresonant pumping.

Another approach is to use fibers with large nonlinear efficiencies. Microstructured optical fibers (MOFs) offer the advantage of having reduced effective areas, thus ensuring a stronger light confinement inside the fiber core, which increases the nonlinearity compared to bulk fiber. Recently, both alternatives have been combined by using a suspended-core microstructured fiber made of chalcogenide glass to make a BFL [5]. A 3 meter long suspended-core AsSe chalcogenide fiber was used and a lower threshold of 22 mW was obtained.

To obtain an even lower laser threshold, we have replaced the suspended-core chalcogenide AsSe previously used by a microstructured $Ge_{10}As_{24}Se_{68}$ (GeAsSe) fiber having a lower transmission loss.

Microstructured GeAsSe chalcogenide fiber

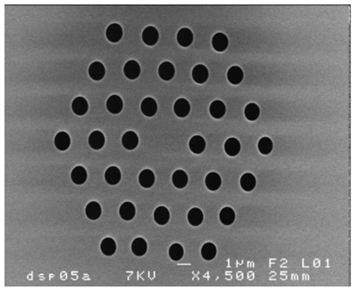

Fig. 1: Transverse section of the microstructured GeAsSe fiber.

The GeAsSe microstructured fiber (fig. 1) used is prepared with high purity glass. A $Ge_{10}As_{24}Se_{68}$ glass rod is previously purified thanks to several synthesis steps using a small amount of oxygen and hydrogen getter. Then, the preform is prepared by using a casting method [6]. The chalcogenide glass is heated around 500 ◦C and flowed into a silica mould which contains aligned silica capillaries. This method enables the realization of low loss fibers. During the drawing step, the hole sizes are adjusted by applying a positive pressure in the perform [7].

The external diameter of the AsSe suspended-core fiber is 240 *µm* and the core diameter d is 3.8 *µm*. The mode effective area was estimated to be around 8 µm² and the fiber losses *α* were found to be 0.65 dB/m at 1.55 *µm*.

Brillouin scattering in the microstructured GeAsSe chalcogenide fiber

A complete experimental characterization of Brillouin scattering in our GeAsSe MOF was realized. A g_B of 4.5×10^{-9} m/W was determined using the setup and method detailed in [8]. A spectral characterization of the Brillouin Gain spectrum was also done using a heterodyne detection from which a Brillouin frequency shift ν_B of 7.25 GHz and a Brillouin gain linewidth $\Delta\nu_B$ of 17 MHz were measured. The values of g_B, ν_B and $\Delta\nu_B$ are slightly different from the measured values for a suspended-core AsSe fiber [5]. This can be explained by the presence of germanium in the fiber composition [9].

Brillouin fiber laser

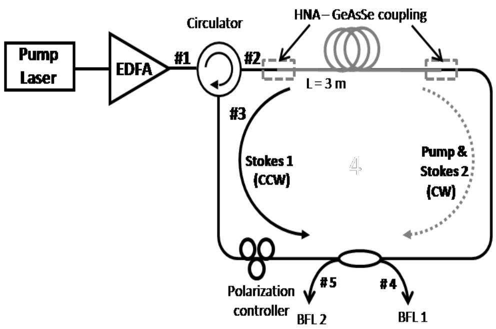

Fig. 2: Experimental setup for the GeAsSe BFL. Abbreviations are as follows: EDFA (Erbium Doped Fiber Amplifier); HNA (High Numerical Aperture); CW (Clockwise); CCW (Counterclockwise).

The experimental setup of the single-frequency BFL used in this letter is pictured in Fig. 2. The laser cavity is composed of 3 m of GeAsSe fiber and 5 m of SMF28 fiber resulting in a total optical cavity length of 14.6 m (5 × 1.45 + 3 × 2.45) This corresponds to a free spectral range (FSR) of 20.5 MHz, which is more than the measured Brillouin gain bandwidth (17.6 MHz), which can ensure that only one single longitudinal mode is oscillating inside the cavity. The output of the BFL is extracted from a 10 % fiber coupler while the remaining 90 % is fed back into the cavity. The ring cavity is closed by an optical circulator thus allowing free propagation of the Stokes waves, which perform multiple roundtrips, while the pump wave interacts only over a single loop. The main advantage of this cavity over a conventional ring resonator cavity [10] is that there are no resonant conditions for the pump, and thus, no need to servo-lock it with a feedback loop. A polarization controller is inserted inside the cavity to ensure that the polarization of the pump is kept parallel to that of the Stokes wave to yield maximum Brillouin gain since our fiber is not polarization-maintained. The total round-trip linear losses, which includes 1.8 dB due to transmission losses in the chalcogenide fiber, 3.5 dB of coupling losses and 2.5 dB across the optical components in the ring cavity, is estimated to be around 7.8 dB.

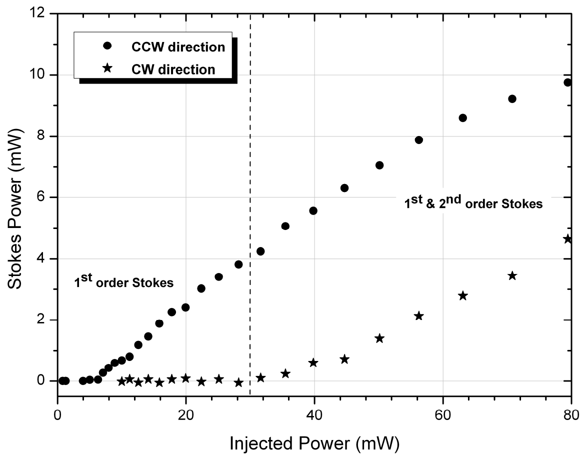

Fig. 3: BFL output power as a function of pump power

Fig. 3 illustrates the BFL output Stokes power as a function of the injected pump power in the chalcogenide fiber. Since the pump power is launched in the clockwise (CW) direction with respect to figure 2, the S1 lasing (BFL1) propagates in the counterclockwise (CCW) direction and is coupled out of the ring cavity at port # 4 of the coupler. In the region below 30 mW, the measured Stokes power is approximately proportional to the pump power, indicating Brillouin lasing on the first Brillouin shift with around 25 % slope efficiency and a very low threshold of about 6 mW for single pass pumping. S2 is reached when the injected pump power in the chalcogenide fiber exceeds 30 mW. At this point, the optical power generated from the S1 exceeds the Brillouin threshold of the fiber and creates a second SBS gain in its opposite direction. The S2 Brillouin laser thus obtained copropagates with the pump wave in the CW direction and can be extracted from the cavity via the port #5 of the coupler.

Above this 2[nd] threshold any increase in the injected pump power normally only increases the output power of S2. Hence, the CCW measured output ceases to increase while the CW output increases linearly with a slope of 11%. This is however not what is observed on the experimental plot: the measured power of CCW output (BFL1) increases but at a slower rate with a tendency to reach saturation. This can be explained by the fact that only part of the optical power of the 1st Stokes wave is used to generate the 2nd order Stokes. This result in an undepleted pump contribution, probably due to the small amount of fiber length used, which contributes to the increase of the output power measured in the CCW direction.

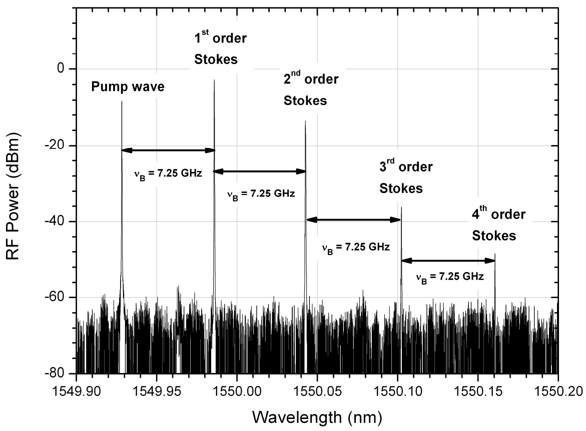

Fig. 4: Brillouin laser output spectrum measured with an optical spectrum analyzer for an injected pump power of 120 mW.

The optical spectrum of the BFL was also monitored. Fig. 4 shows the optical spectrum of the Brillouin laser output measured by combining the output # 4 and # 5 by a 3-dB coupler. A strong S1 line with a downshift of 7.25 GHz with respect to the pump frequency is observed when the injected pump power exceeds 6 mW. A 2nd order Stokes component is obtained for a pump power of around 30 mW. These results confirm the threshold power of the S1 and S2 BFL measured earlier. Higher orders of Stokes components can be generated in the fiber laser cavity. We have obtained up to 4th order Stokes components for a maximum injected pump power of 150 mW. However we have yet to determine whether the 4th order Stokes is solely created from Stimulated Brillouin scattering in the fiber or comes from four-wave mixing due to the simultaneous existence of the other orders of Stokes within the ring cavity [11].

This result implies that a multiorder Brillouin laser can be obtained with only a few meters of chalcogenide fiber at a reasonable pump power without further amplification in the BFL ring cavity.

Conclusions

In conclusion, a Brillouin fiber laser made of microstructured chalcogenide GeAsSe fiber and operating on the 2nd order Stokes has been demonstrated for the first time to our knowledge. This laser has a very low threshold of 6 mW for 1st order Stokes lasing and 30 mW for 2nd order Stokes conversion. We hope to achieve even lower laser threshold for the 1st and 2nd order conversion, of the order of the milliwatt, by resonant pumping in our cavity, provided a Pound-Drever-Hall frequency-locking technique is used [12].

Acknowledgements

This work has been partially funded by the FEDER and French territorial and governmental organizations (Région Bretagne, LTA and CG22) through the “Sea Innovation & Business Cluster (Pôle Mer)” in the framework of ATOS project and also through the PONANT project.

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